Adventures in Geoelectric Field Calculation and Validation

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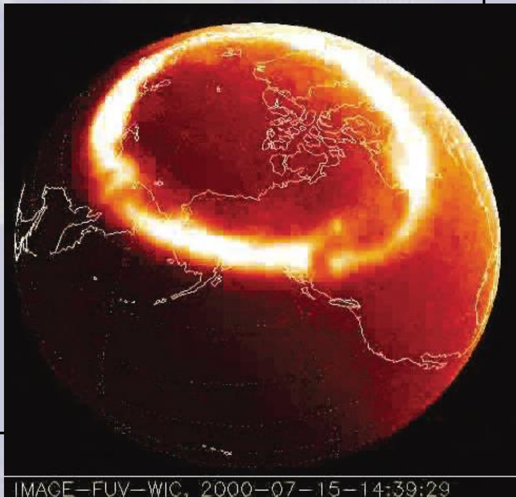
Outline

- Motivation – Policy & User Needs
- Geoelectric Field Calculation
- Validation Results
- Future Plans & Work in Progress

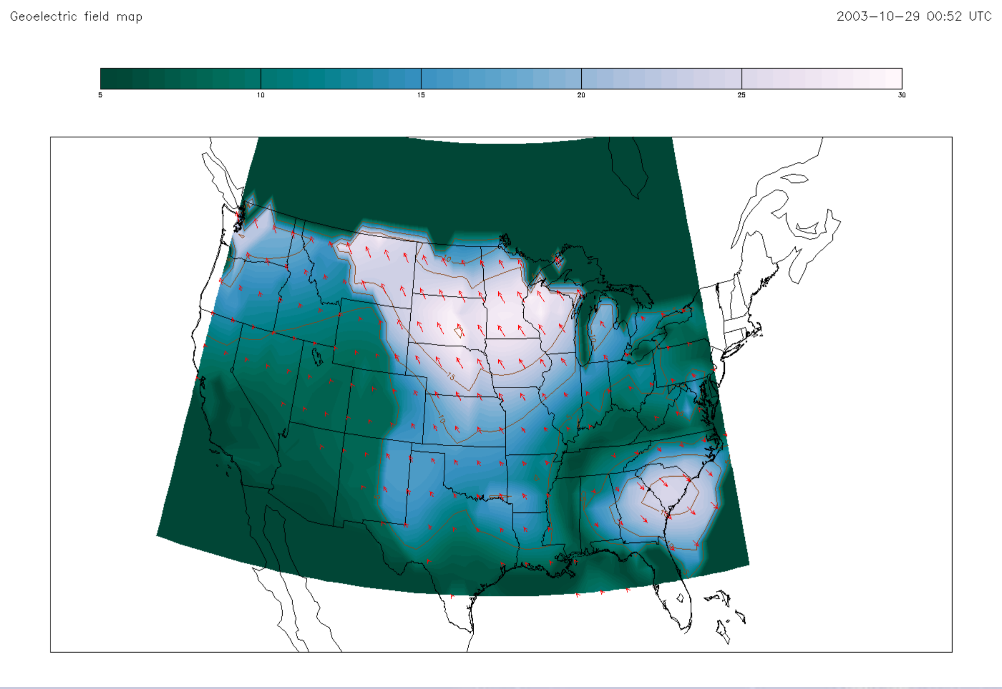


Policy Milestones

- ***House Committee Meeting on Space Weather:** agency roles, impact on the electrical grid (October 30, 2003)*
- ***Office of Federal Coordinator** - Assessment Committee for the National Space Weather Program (May 2006)*
  - *"..the nation's vulnerability to space wx is an issue of increasing concern.."*
- ***Workshop & Report by the National Academies** – Societal and Economic Impacts of Severe Space Weather Events (2008)*
- ***DOE/NERC workshop:** High-Impact, Low Frequency Event Risk to the North American Bulk Power System (November 2009)*
- ***JASON report (DHS sponsored):** Impact of Severe Space Weather on the Electric Grid (2011)*
- ***NERC Geomagnetic Disturbance Task Force:** Organized to develop guidelines and expertise regarding GMD (starting in 2011)*
- ***FERC Order No. 779** – directs NERC to develop standards for updated operating procedures and to carry-out vulnerability assessments (2013)*
- *See also: Jonas & McCarron, Space Weather, 2015*

Well Established User Need

- Motivation: Space Wx Workshop 2011 focus on Electrical Grid Impacts
- Key Finding: Users need nowcast and forecast the Geoelectric Field
- Application: Given the Geoelectric field, users can calculate the geomagnetically induced current (GIC) using system models and assess/understand impacts



Geoelectric Field Calculation

Long Term Goals:

Nowcast:

- **Use real-time magnetometer data as the input**
- **Interpolate geomagnetic variations on a spatial grid (latitude/longitude)**
- **Calculate Electric Field using best available conductivity models**

Forecast:

- **Geospace model predicts local magnetic field variations**
- **Calculate the corresponding Electric Field at each point**

Two key components

- The External Driver (Space Weather)
  - Time varying currents in the ionosphere & magnetosphere driven by solar wind interactions
- The Geological Conductivity Structure
  - Naturally induced currents below Earth's surface
  - Significantly modifies impact of Space Wx driver
- Filter Analogy
  - B-field variations are input signals
  - Earth conductivity alters amplitude and phase of input signals as a function of frequency
  - E-field is the resultant output signal

E-field Calculation – frequency domain

- The Horizontal Components of the Geoelectric Field at the surface are related to the Horizontal Components of the Geomagnetic Field at the surface by means of a frequency dependent impedance tensor:

$$\begin{bmatrix} E_x(f) \\ E_y(f) \end{bmatrix} = \begin{bmatrix} Z_{xx}(f) & Z_{xy}(f) \\ Z_{yx}(f) & Z_{yy}(f) \end{bmatrix} \begin{bmatrix} H_x(f) \\ H_y(f) \end{bmatrix}$$

- f is frequency (Hz)
- $\mathbf{E}$ is the electric field (V/m)
- $\mathbf{B} = \mu\mathbf{H}$ is the magnetic induction (Tesla)
- The 'transfer function' Z changes the amplitude and phase of the input signal H in a way that varies with frequency

E-field Calculation – Discrete Fourier Transform

- In applications we take a forward DFT of the B-field time series to get a representation in terms of frequency components:

  $B_{\boldsymbol{x}}(f_k) = \sum_{m=0}^{N-1} e^{-i2\pi f_k t_m} B_{\boldsymbol{x}}(t_m)dt,$

  $B_{\boldsymbol{y}}(f_k) = \sum_{m=0}^{N-1} e^{-i2\pi f_k t_m} B_{\boldsymbol{y}}(t_m)dt,$ with k=1,2,…,N-1

- We use the 'transfer function' equation (last slide) to calculate $E_x(f_k)$ and $E_x(f_k)$, the frequency components of the Geoelectric field

- Then we take the inverse DFT to deduce the E-field time series:

  $E_x(t_m) = \sum_{k=0}^{N-1} e^{i2\pi f_k t_m} E_x(f_k)df,$

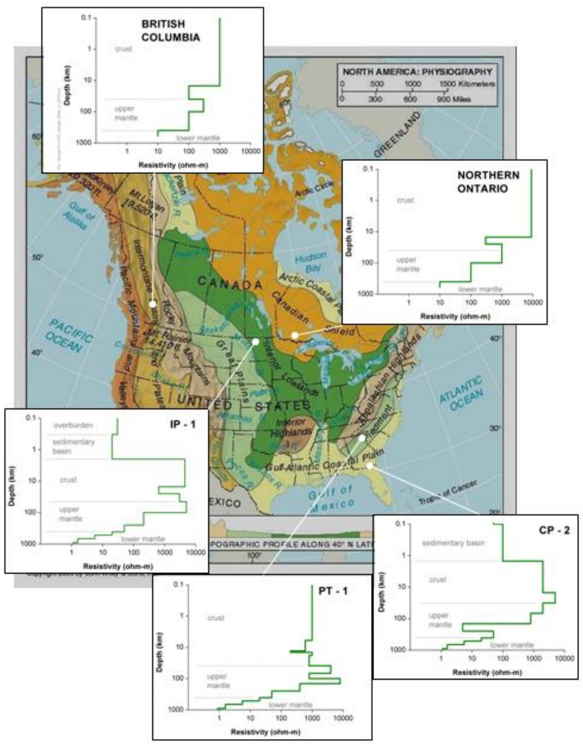
  $E_{\boldsymbol{y}}(t_m) = \sum_{k=0}^{N-1} e^{i2\pi f_k t_m} E_{\boldsymbol{y}}(f_k)df,$ with m=1,2,…,N-1

- Keeping in mind that f_k for $k >$ N/2 are aliases for the negative frequencies k-N

How do we get the Transfer Function?

- **Plan A:**
  - Use an approximate, depth-dependent conductivity model
  - The relationship between surface E and B fields can be inferred by analysis of E & B field waves that reflect and refract across the layer boundaries (e.g. Simpson & Bahr 2005)
- **Plan B:**
  - Use an empirically inferred transfer function from a magneto-telluric survey
  - Although the motivation for the MT survey is to study solid Earth geophysics, the GIC application benefits directly from the derivation of the transfer functions, which is a primary product of this kind of work (e.g. Egbert, 2007)

Initial Efforts - 1D Conductivity Models

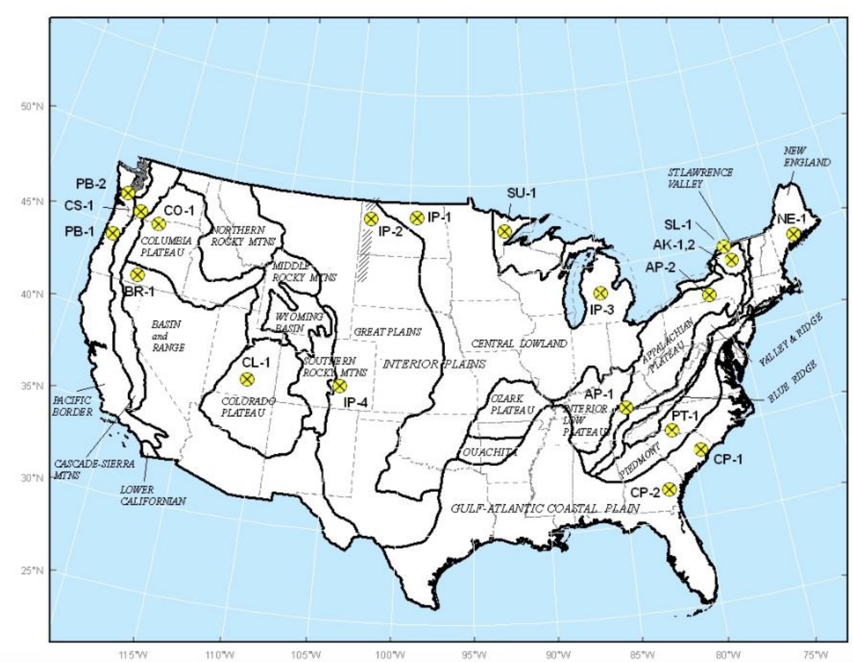


Fernberg (2012)

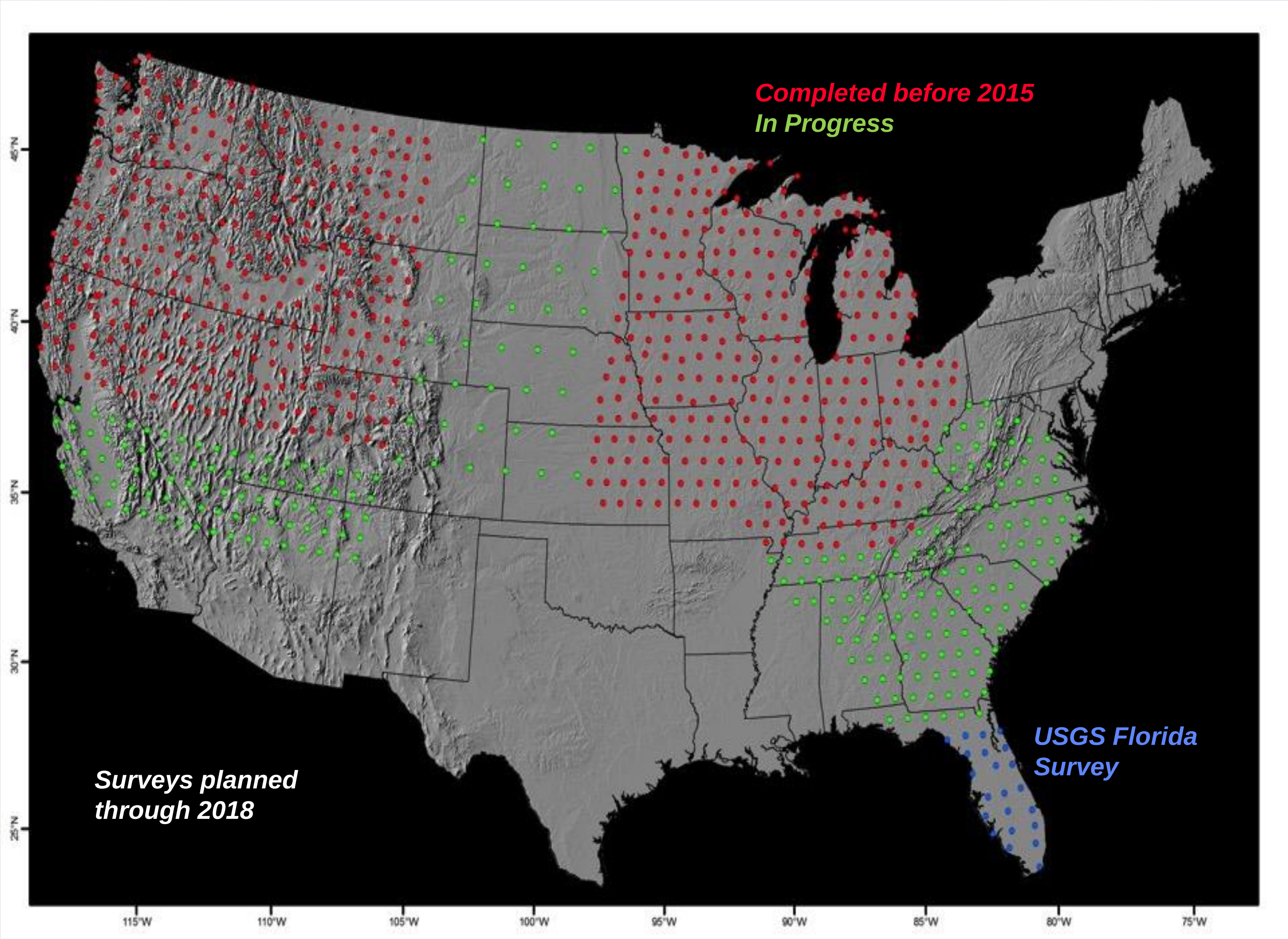
- **1D Conductivity profiles for ~20 different physiographic regions**
- **Based on a compilation of previously published information**

- **Fernberg acknowledges that these are only first-order approximations**
- **Numerous limitations & cautions also appear throughout the report**

Figure 6: Location of 1-D earth resistivity models with respect to physiographic regions of the contiguous United States [6].



MT results: NSF Earthscope Survey & USGS work



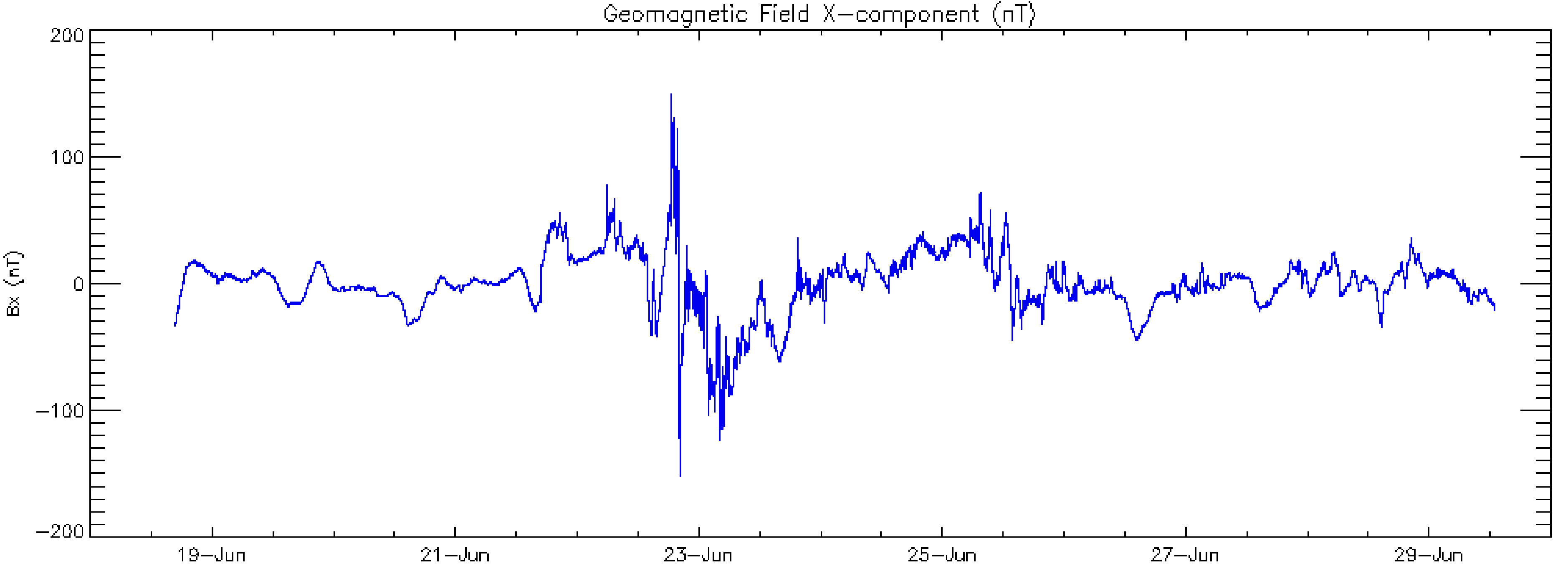
Surveys are accomplished through temporary "transportable" array deployments of ground-based geomagnetic and geoelectric sensors.

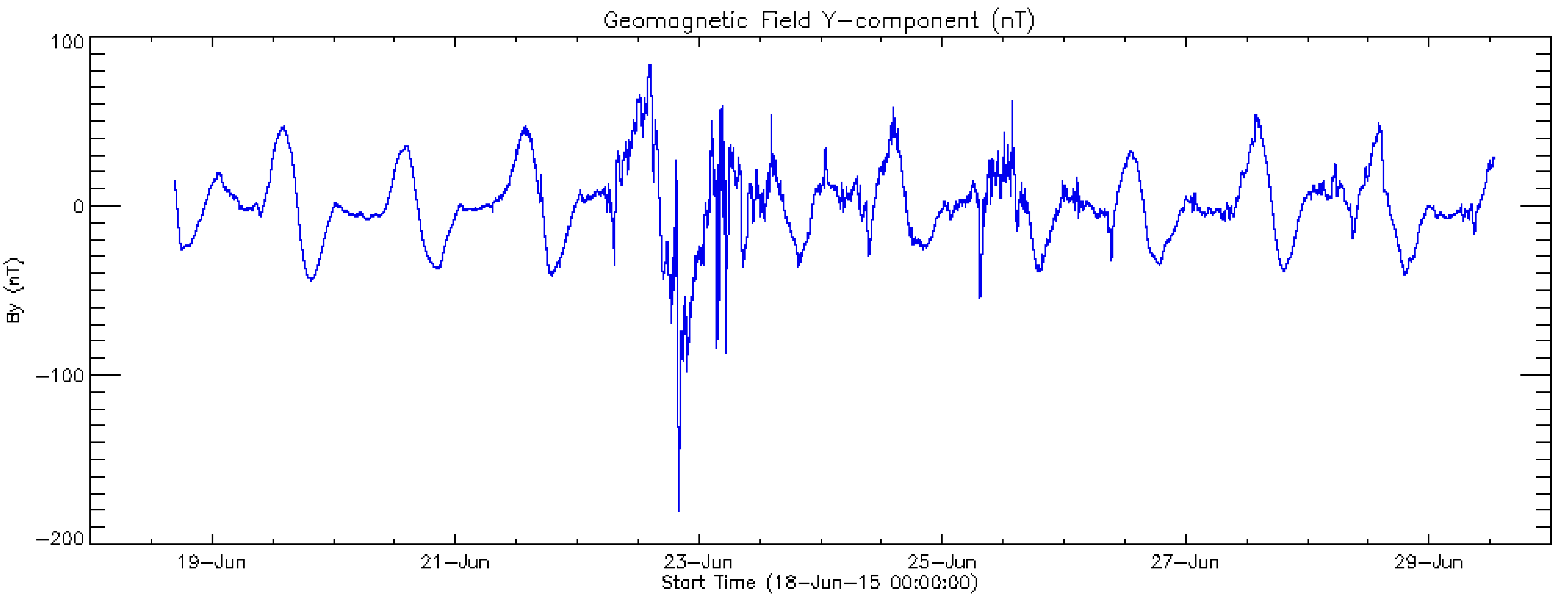
Credit: Bedrosian, Kelbert

Earthscope: Schultz 2009

Case Study – ALW48b

- Earthscope survey site: 19-30 June 2015
- Location in northern Alabama
- Kp=8+ storm on 22-23 June
- Outputs from the MT survey:
  - One-second B and E field measurements
  - Empirical Impedance tensor
- Results for this case study:
  - Compare observed and calculated E fields for validation
  - Compare accuracy of E-field computation using 1D conductance models


Geomagnetic Field X-component (nT)
200
100
0
−100
−200
Bx (nT)
19−Jun
21−Jun
23−Jun
25−Jun
27−Jun
29−Jun


Geomagnetic Field Y-component (nT)
100
0
−100
−200
By (nT)
19−Jun
21−Jun
23−Jun
25−Jun
27−Jun
29−Jun
Start Time (18−Jun−15 00:00:00)

Impedance & Apparent Resistivity

We represent the impedance (transfer function) as apparent resistivity:

$$\rho = \frac{0.2}{f} * |Z(\omega)|^2$$ (Vozoff, 1972)

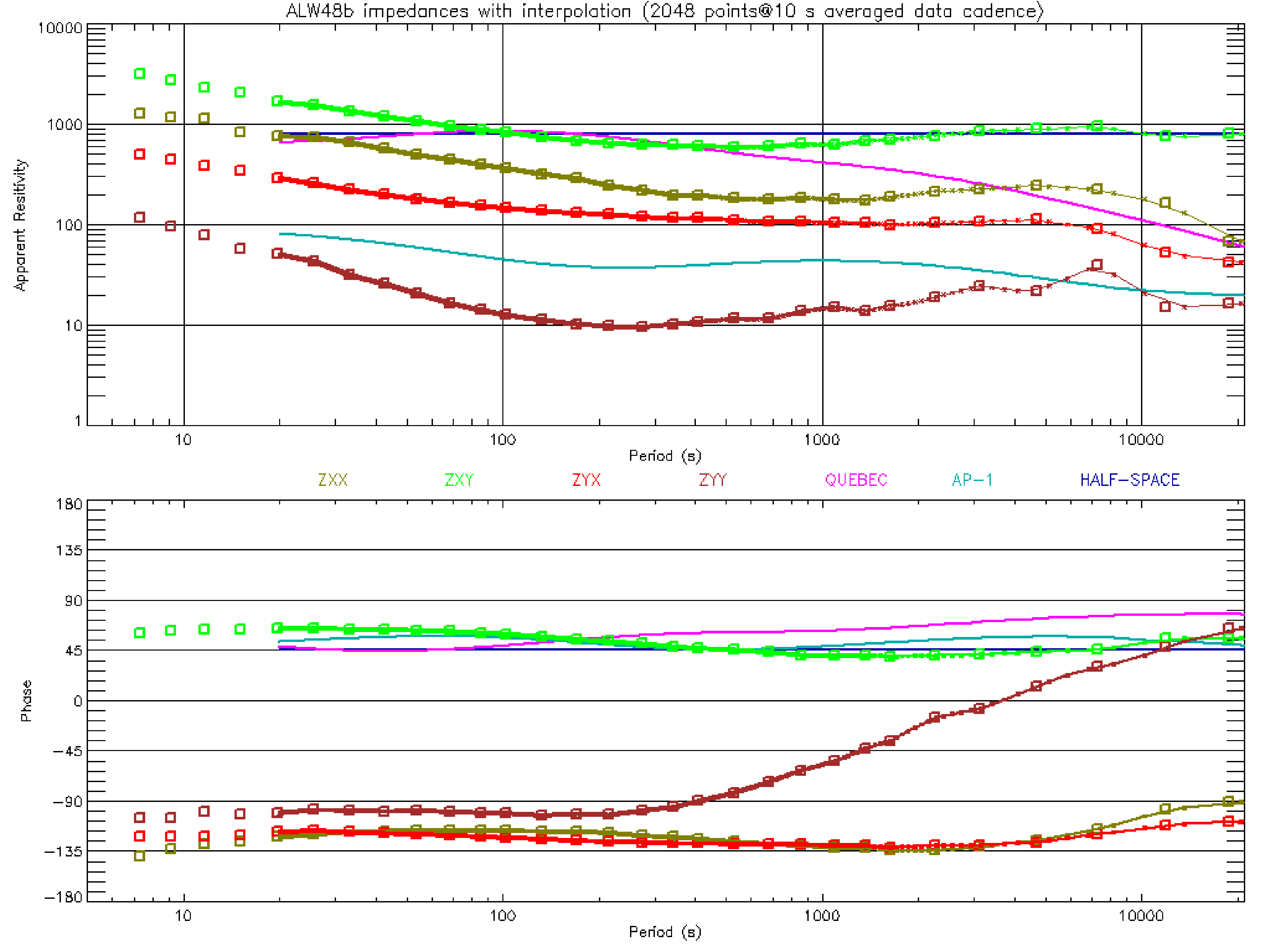
Layer	Thickness (km)	Resistivity (Ωm)
1	4	80
2	12	80
3	25	20
4	14	300
5	45	100
6	150	10
7	160	50
8	110	20
9	150	5.6
10	230	1.58
11	∞	0.89

Fernberg AP-1 1D model

Layer	Thickness (km)	Resistivity (Ωm)
1	15	20000
2	10	200
3	125	1000
4	200	100
5	∞	3

Quebec 1D model

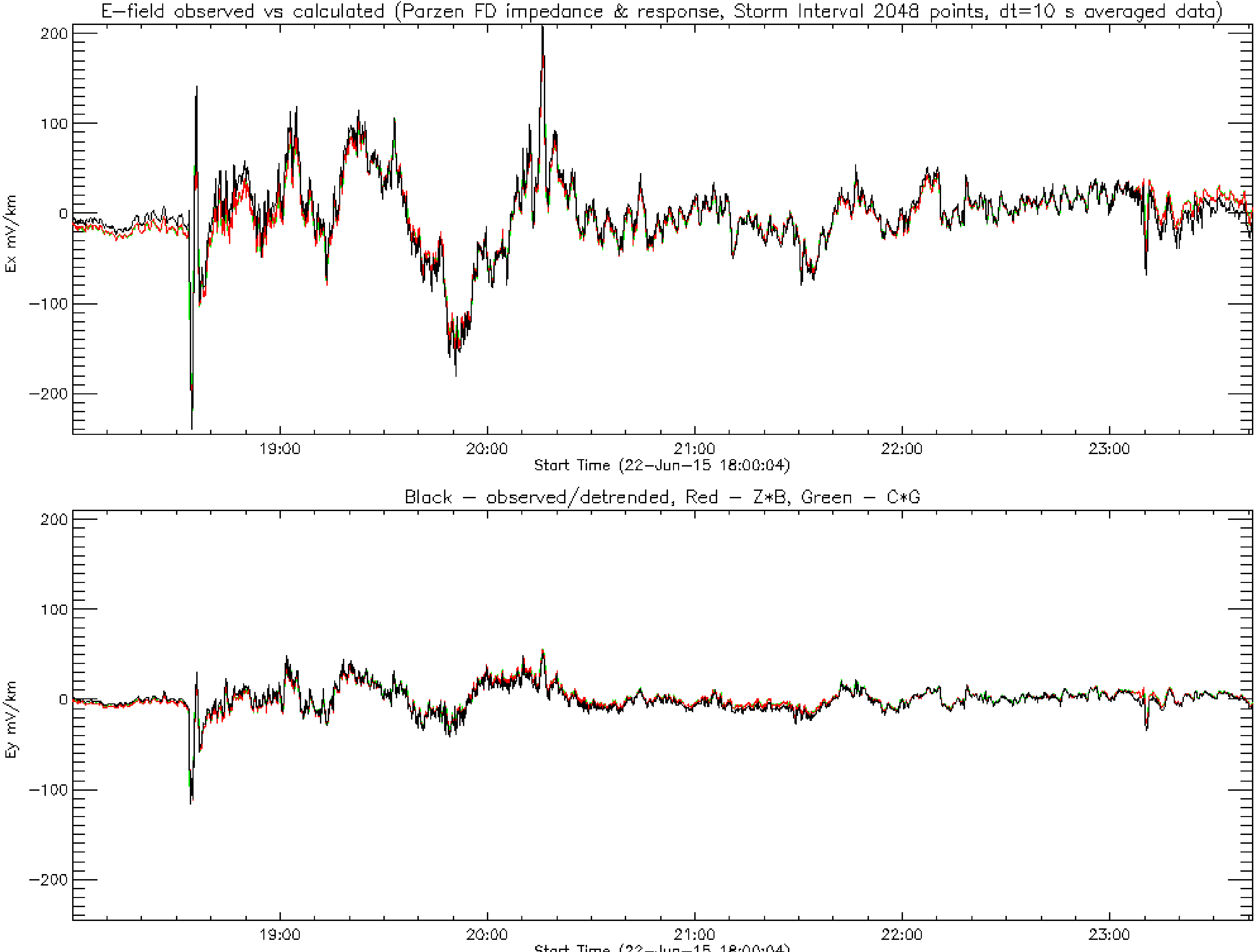
We compare the apparent resistivity of uniform half space, the nearest Fernberg model (AP-1), and the Quebec 1D model with the empirical (survey) impedance components

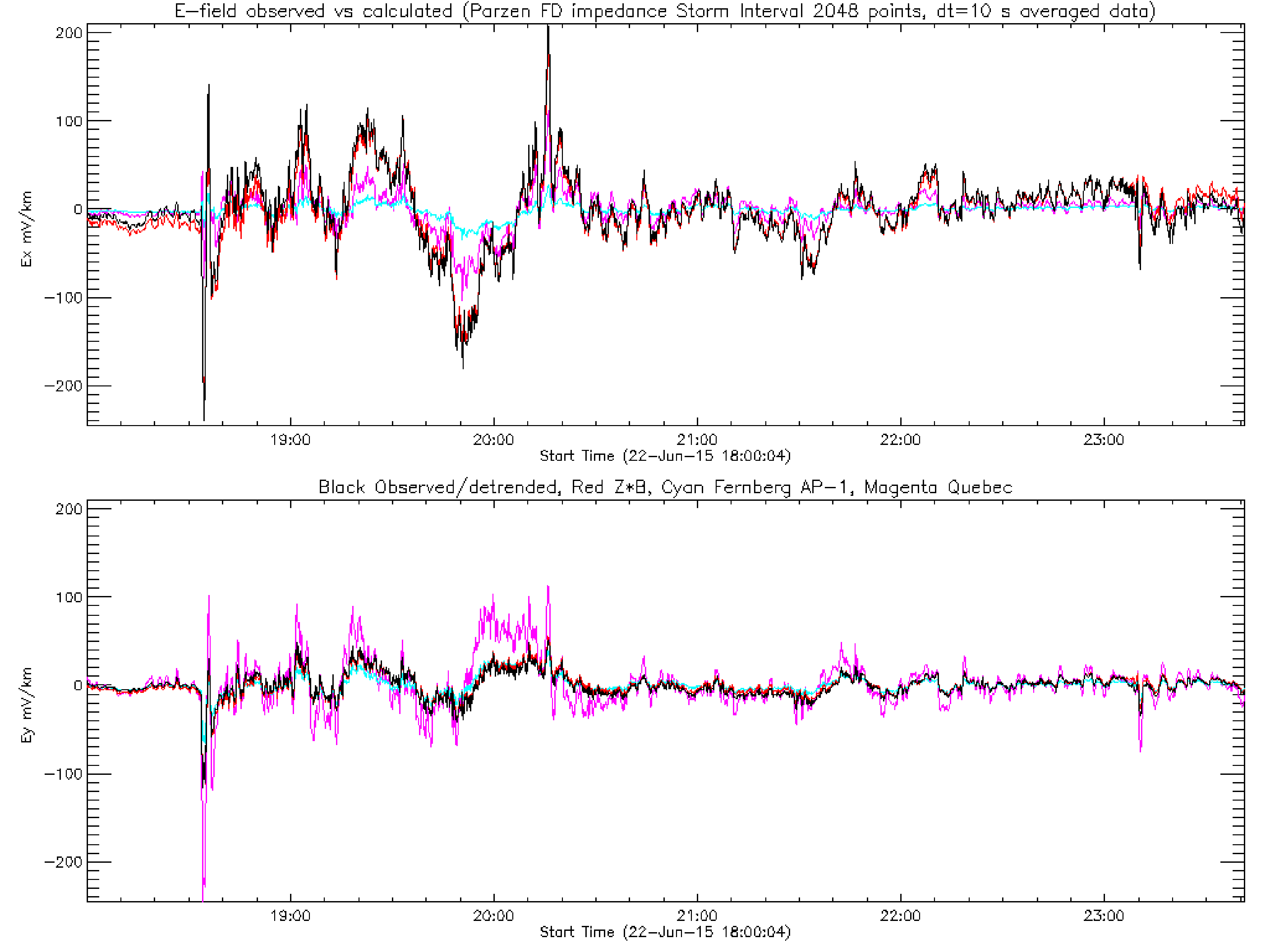


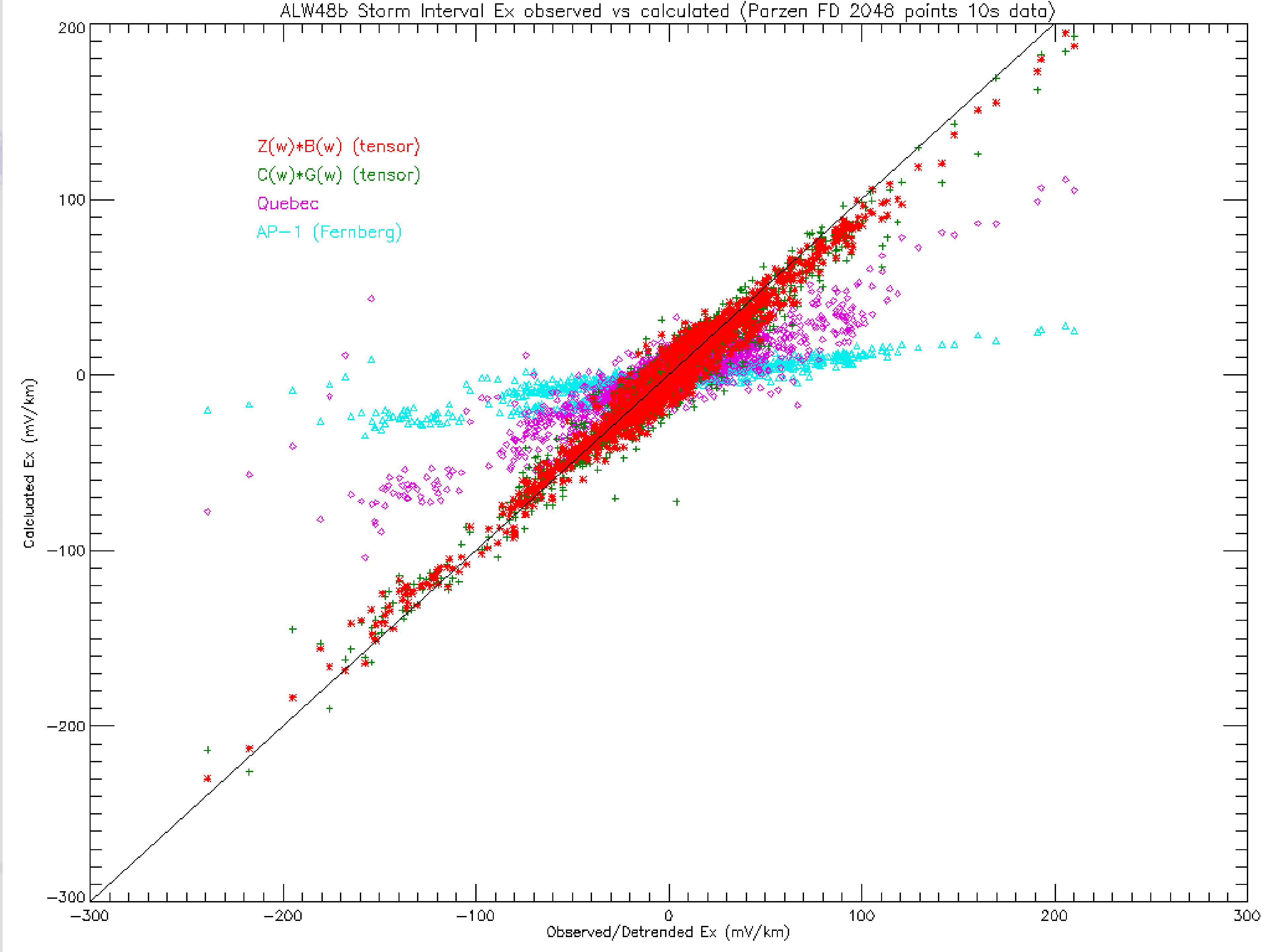
ALW48b impedances with interpolation (2048 points@10 s averaged data cadence)
Apparent Resitivity
10000
1000
100
10
1
10
100
1000
10000
Period (s)
ZXX
ZXY
ZYX
ZYY
QUEBEC
AP-1
HALF-SPACE
Phase
180
135
90
45
0
-45
-90
-135
-180
10
100
1000
10000
Period (s)

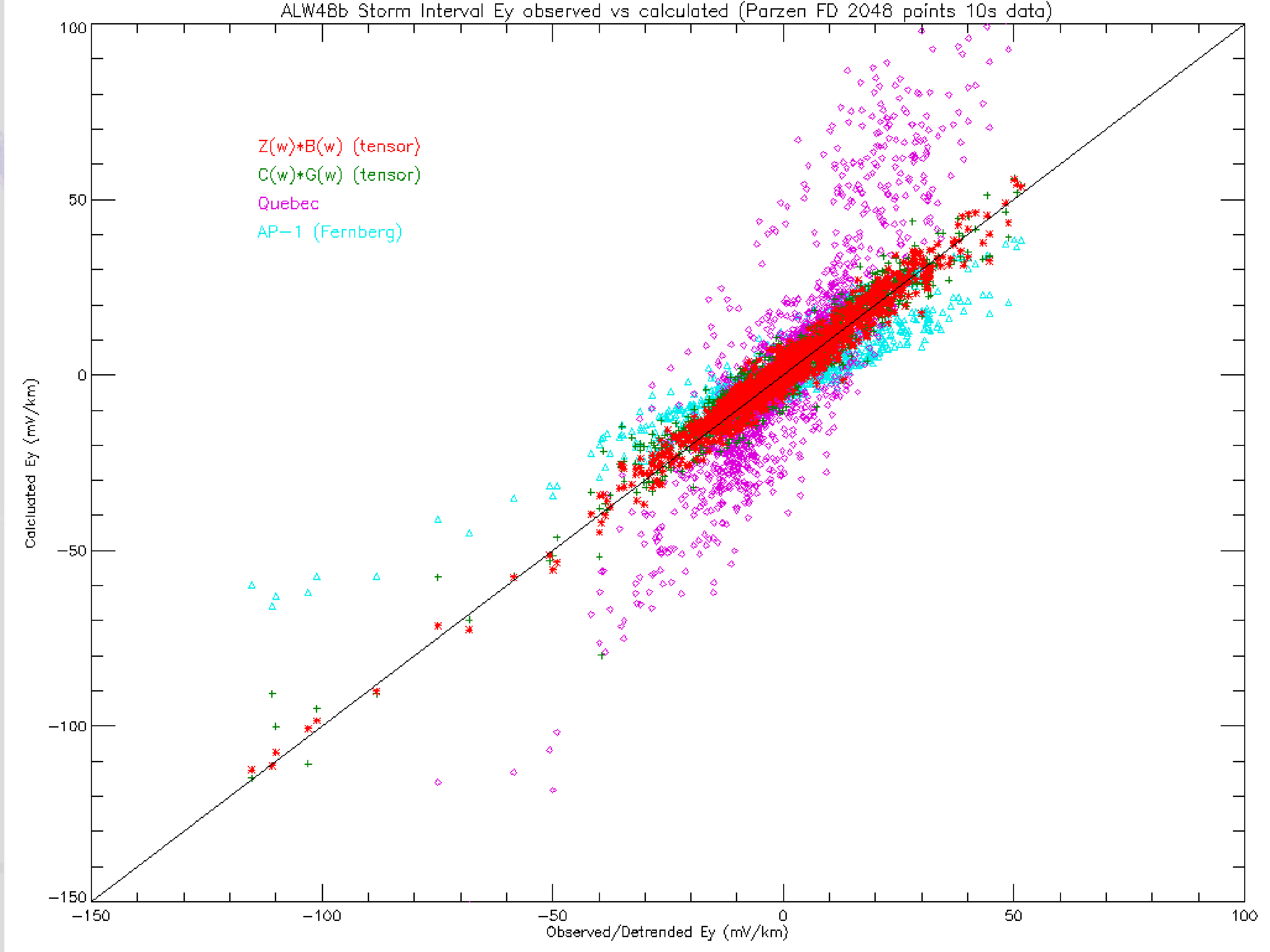
Comparison of Calculated & Observed E

- We take 10 second averages of the B-field and E field data
- E-field values are calculated from B-field using the empirical transfer function
- The observed E-field data is detrended by subtracting the overall mean value
- A window of 2048 points at 10 second cadence is used (about 5.6 hours)


E–field observed vs calculated (Parzen FD impedance & response, Storm Interval 2048 points, dt=10 s averaged data)
Ex mV/km
200
100
0
−100
−200
19:00
20:00
21:00
22:00
23:00
Start Time (22–Jun–15 18:00:04)
Black – observed/detrended, Red – Z*B, Green – C*G
Ey mV/km
200
100
0
−100
−200
19:00
20:00
21:00
22:00
23:00
Start Time (22–Jun–15 18:00:04)


E–field observed vs calculated (Parzen FD impedance Storm Interval 2048 points, dt=10 s averaged data)
Ex mV/km
200
100
0
−100
−200
19:00
20:00
21:00
22:00
23:00
Start Time (22–Jun–15 18:00:04)
Black Observed/detrended, Red Z*B, Cyan Fernberg AP–1, Magenta Quebec
Ey mV/km
200
100
0
−100
−200
19:00
20:00
21:00
22:00
23:00
Start Time (22–Jun–15 18:00:04)


ALW48b Storm Interval Ex observed vs calculated (Parzen FD 2048 points 10s data)
Z(w)*B(w) (tensor)
C(w)*G(w) (tensor)
Quebec
AP−1 (Fernberg)
Calculated Ex (mV/km)
Observed/Detrended Ex (mV/km)
200
100
0
−100
−200
−300
−300
−200
−100
0
100
200
300



ALW48b Storm Interval Ey observed vs calculated (Parzen FD 2048 points 10s data)
Z(w)*B(w) (tensor)
C(w)*G(w) (tensor)
Quebec
AP−1 (Fernberg)
100
50
0
−50
−100
−150
Calculated Ey (mV/km)
−150
−100
−50
0
50
100
Observed/Detrended Ey (mV/km)

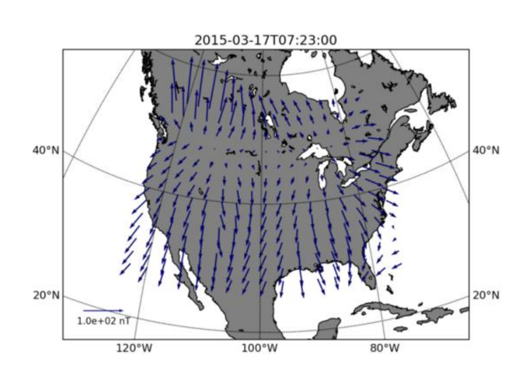
Metrics using the detrended observations

	RMS	Mean	Min	Max	CC
Ex observed	0	0.0	-239	210	1
Z*B	8.1	-2.0	-230	195	0.98
Quebec	25.7	-0.2	-104	111	0.89
Fernberg	35.6	-0.7	-34	28	0.86

	RMS	Mean	Min	Max	CC
Ey observed	0	0.0	-115	52	1
Z*B	3.0	0.7	-113	56	0.98
Quebec	18.0	1.2	-245	113	0.89
Fernberg	6.8	0.4	-66	39	0.90

ΔB-field interpolation

- **Currently in development: SECS interpolation** **(Pulkkinen et al. 2003 and references therein)**
- **NASA/CCMC provided original code**
- **USGS leading operationalization of the code**
- **Goal is to improve local specification by calculating B-fields on a geographical grid**
- **Assessment of accuracy & comparison with other techniques is also on the ‘to-do’ list**



Present & Future of this work

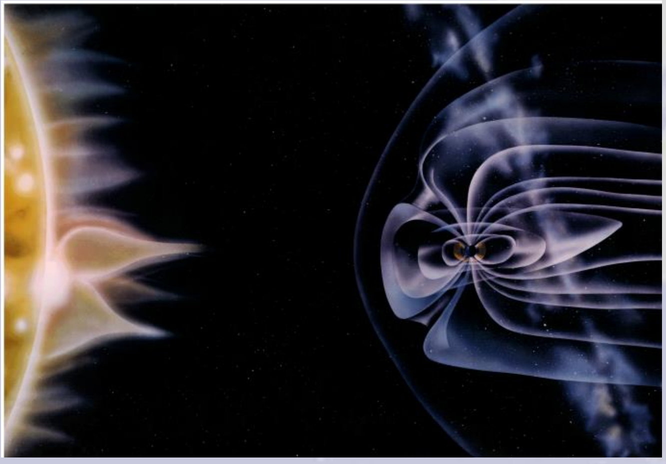
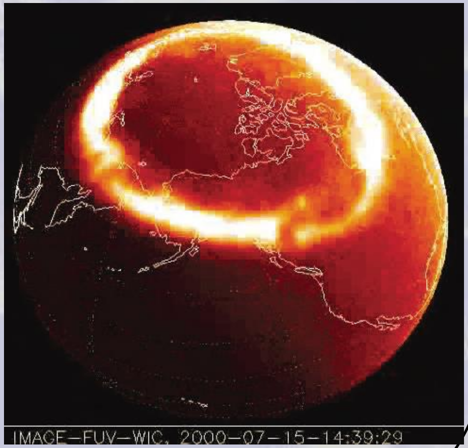
- Real-time E-field prototype in development
  - Selected observatories & appropriate 1D models
  - Plan to incorporate Earthscope results where possible
- Validation work to continue
  - Additional case studies
  - Testing time-domain solutions
- USGS to develop transfer function product
  - Synthesis of 'best available' information to provide transfer functions on geographic grid
- Plan to provide E-field on a geographic grid using B-field interpolation, transfer functions, and validated, real-time calculations

Summary

- Validation results are in progress
- The calculation methods work well when you have accurate transfer functions
- Correlation stays fairly high with approximate models, suggesting a particular user in a particular region could scale the calculated values to compensate for over/under estimation of E-field values in these situations
- The work suggests the importance of completing the MT surveys for the remainder of the U.S., especially regions of relatively dense electrical power infrastructure
- Improvements in the works:
  - Complete time-domain method development
  - Incorporate improved transfer functions where possible
  - Use SECS interpolated ΔB and transfer function database to produce real-time E-fields on a map
  - Development of forecast versions from the Geospace Model

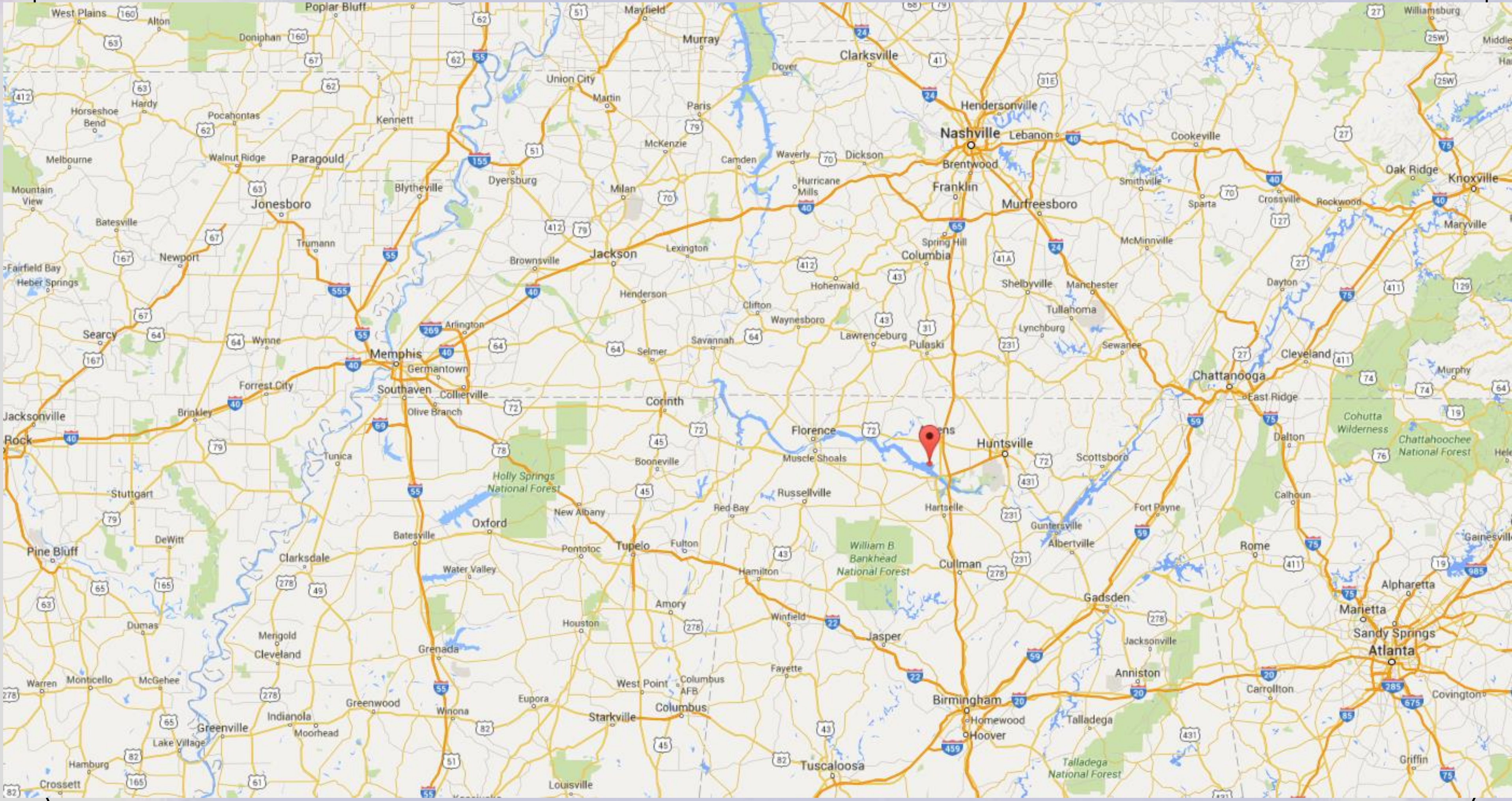
Questions?

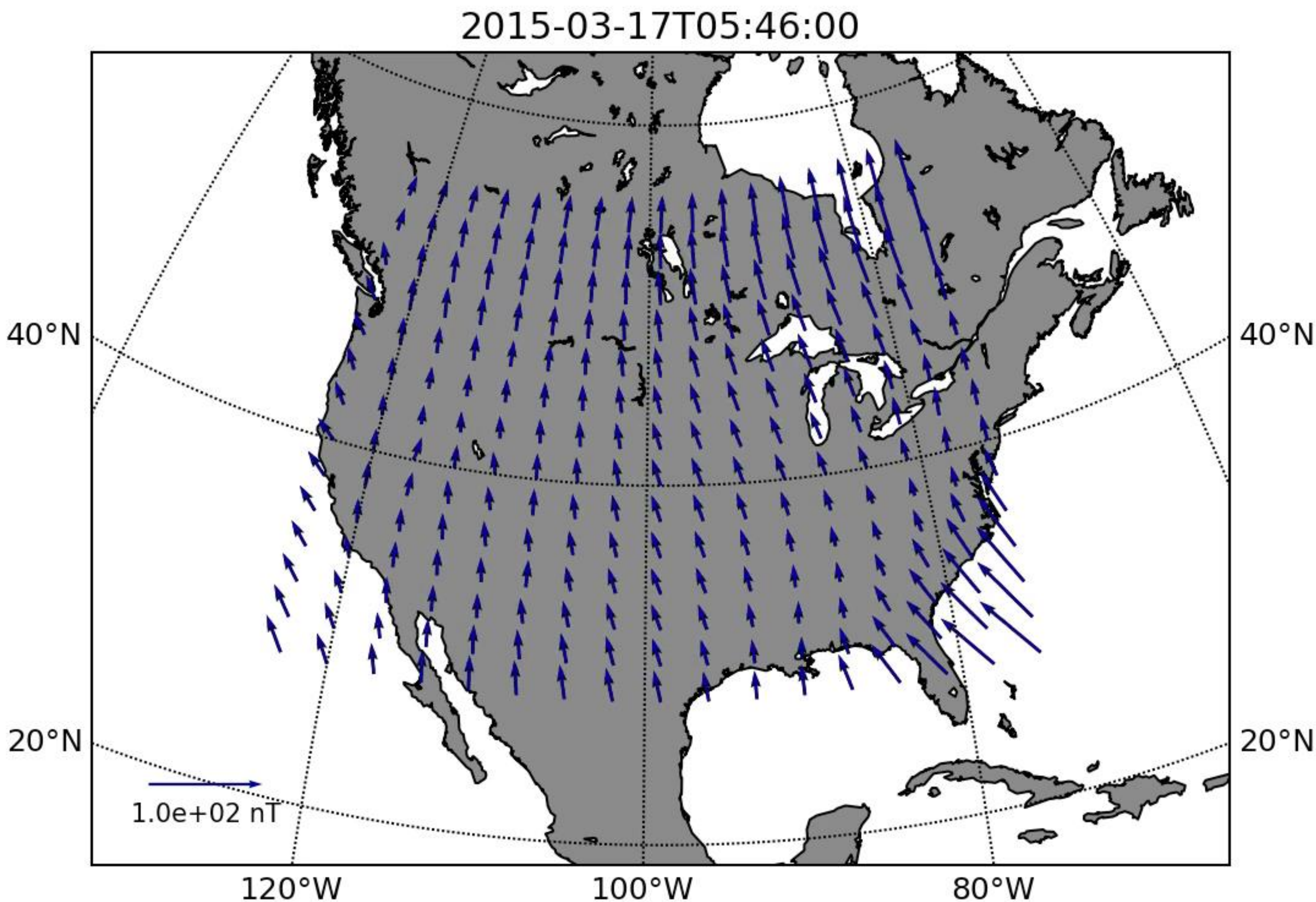


Supplemental Slides

Case Study – ALW48b





2015-03-17T05:46:00
40°N
40°N
20°N
20°N
120°W
100°W
80°W
1.0e+02 nT

Calculating E – frequency domain method

- Based on the model, we have a relationship between frequency components of E and B:

$$\mathrm{E_x}(\omega) = \mathrm{C}(\omega) \times i\omega\mu H_y(\omega)$$

- A fairly standard approach is to transform B (or dB/dt) to frequency domain using FFT, carry out the multiplication, and transform E back to time domain
- Applying FFT to discrete time series data is affected by the following parameters:
  - The duration of the analysis interval – T
  - The sampling interval – dt
- The number of samples is N = T/dt
  (choose T to make N an integer)
- This will set the frequency resolution df to 1/T

Conductivity Boundaries